REAL-TIME ACQUISITION AND MEASUREMENT OF ECHOLOCATION SIGNALS EMITTED BY WILD ATLANTIC SPOTTED DOLPHIN, *STENELLA FRONTALIS*, UTILIZING HYDROPHONE ARRAYS WITH SIMULTANEOUS UNDERWATER VIDEO.

W.W.L AU AND D.L. HERZING

ABSTRACT

A technique using multi-element arrays of hydrophones with underwater video recording was developed as a tool to accurately measure echolocation signals of free-swimming dolphins. Two configurations of hydrophones, including a line array of three hydrophones spaced at 30 cm and a symmetrical star configuraton of four hydrophones spaced at 45.7 cm, were used. The arrays were held by a skin diver while dolphins oriented on the arrays. Video and acoustic signals were cabled back to the boat. A real-time analog/digital data acquisition system operating at 500 kHz was used to detect, digitize, and store echolocation signals. Spotted dolphin echolocation signals had bimodal frequency spectra with frequency peaks at 40-60 kHz, and 120-140 kHz. Peak to peak source levels up to 210 dB re 1 *u*Pa were measured. Bandwidth clustered around 40 kHz. This system was productive as a portable field tool for acquiring and measuring, real-time, echolocation signals of free-ranging dolphins.

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13. ABSTRACT (Maximum 200 words)

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Real-Time Measurements of the Echolocation Signals of Wild Dolphins.

Procedure

The echolocation signals of *Stenella frontalis* (Atlantic spotted dolphins) were measure near the surface using a line array of three hydrophones (1996) and an array of four hydrophones in a symmetrical star configuration (1997) with an attached video camera as shown in the schematic of Fig. 1. In the field test of 1996 we were able to ground truth the data acquisition system using multiple hydrophones and simultaneous analog-to-digital conversion. In both 1996 and 1997 we obtained base-line echolocation data of *Stenella* in the free field. Due to the difficulty of 1) presetting the unit in the sand bottom during active bottom foraging, 2) equipment difficulties, and 3) uncooperative weather conditions during some attempts, no signals were acquired during the digging for prey on the bottom.

For the initial system in 1996 the hydrophones were spaced 30-cm apart and the video camera was oriented directly above the center hydrophone and directed perpendicular to an imaginary line connecting the hydrophones. The depth of the hydrophones was approximately 0.8 m. In 1997 the symmetrical star configuration system was used. The spacing between the center hydrophone and the other hydrophones was 45.7 cm. A four-channel simultaneous analog-to-digital data acquisition system operating at 500kHz was used. The whole assembly consisting of the array, video camera and hydrophone as well as video and hydrophone cables were supported by a surface float, and the whole assembly was positioned and directed by a swimmer. The amplifier-line driver electronics were housed in an underwater housing located on the float. In some cases the unit was lowered overboard if dolphins were feeding and orienting towards the boat. A 250-ft multiconductor cable along with the video cable were connected between the electronic housing

and the catamaran, Stenella.

On board electronics consisted of a video monitor and camcorder, a multi-channel amplifier and a transportable "lunch-box" type computer. Two GAGE 1210, 12 bit dual simultaneous sampling data acquisition boards were connected to internal slots of the lunch-box computer. The data acquisition system operated with a pre-trigger capability and performed analog-to-digital conversion at a rate of 500 kHz rate. The data collection process for each echolocation signal was triggered by the input from the center hydrophone. The clocks on the video recorder and the data acquisition computer were synchronized

The geometry of the line array is depicted in Fig. 2, with the left and right hydrophones, h_2 and h_3 at equal distance from the center hydrophone h_1. If we let c be the speed of sound in the water and d_h be the separation distance between hydrophones, the location of a sound source in the horizontal plane can be determined by the difference in the time of arrival of the signal at each hydrophone. If t_{21} is the time difference of arrival between h_2 and h_1 and t_{31} is the time difference of arrival between h_3 and h_1 the location of the sound source can be determined by the following equations:

(1)

The equations for d_1 and s_x contain poles so that the solution "explodes" to infinity whenever $t_{21} = -t_{31}$. In reality, whenever t_{21} is close to $-t_{31}$, one can get unrealistically large numbers so that the solution in these cases is not very accurate. We found that when $t_{21} + t_{31} < 8$ s, the solution was not reliable. In those cases, we averaged the solution for the just previous click and the next click as a way of estimating the dolphin's location. The solution of s_y also contain an ambiguity since there are two solutions, one associated with the "+" sign and the other with the "-" sign. However, in our situation, the dolphins were generally in front ot the swimmer so that the solution corresponding to the "-" sign was not realistic.

RESULTS

In 1996, during two days of data collection with a pod of *Stenella*, one of the first trip and another on the second trip, we were able to collect over 20 files of echolocation click data. In 1997 during a 10 day field attempt, we were able to collect over 50 files of Stenella clicks in multiple contexts, including nocturnal feeding. The quality of the data varied from poor (files with a lot of whistles and off axis signals) to very good.

The orientation of an echolocating dolphin could be determined by examining both the waveform and the relative amplitude of the signals received by the three hydrophones. If a dolphin was oriented directly at the center hydrophone, then the amplitude of the signals received by the three hydrophones should either be the same or the center hydrophone should have the highest amplitude signal and the two end hydrophones should receive signals of similar amplitudes. If the relative amplitude of the signals received by the three hydrophones are different, this indicates that the dolphin was not oriented directly at the array since the echolocation beam drops off rapidly

away from the beam axis. Two sequence of higher amplitude click signals received simultaneously by the three hydrophones are shown in Figs. 3 and 4. The parameters on the left side of each figure are the click in a particular data file followed by the time between the occurrence of that click and the previous click, the hydrophone position, along with the peak-to-peak sound pressure level in dB re 1 Pa. The times in s are the arrival time differences of the signals received by the left and right hydrophone relative to the center hydrophone. The relative time of arrival at each hydrophone was determine by finding the point at which the signal has its maximum value, and using that point along with the two previous points and the next two points, and fitting a parabolic curves through the five points. An expression of the maximum point of the parabolic curve can be obtained by differentiating the equation for a parabola with respect to time and setting it equal to zero. The parameters on the right side of each set of three signals are the estimate of the x and y coordinate location of the echolocating dolphin with respect to the geometry of Fig. 2, followed by the absolute range of the dolphin from the center hydrophone. The data of Fig. 3 was for a situation in which the dolphin stayed close to the x=0 axis, directly in front of the video camera approximately 1.2 to 5.9 m away from the array. However, it is important to keep in mind that both the dolphin and the swimmer were constantly moving which caused the orientation of the array to also be changing. The signals in Fig. 4 are examples of changing orientation of the dolphin and the array orientation. The range estimate for click #55 and 60 are examples of nonsensical range estimates caused by the time differences being almost equal but with different signs. It does not make sense for the dolphin to be 5.9 m away on click #54 and then be 16.0 m away on click #55 which occurred 34 ms later. In such a case, we could average the range of the previous and adjacent clicks to get a better range estimate for click #55 and #60 and even #61.

The spectrogram for the clicks shown in Fig. 3 is depicted in Fig. 5. The signal with the highest amplitude in the three signals shown in Fig. 3 , was used to calculate the spectrograms. The spectrograms (from both 1996 and 1997) suggest that the clicks emitted by *Stenella frontalis* have a tendency to be bimodal, having two distinct peaks, one at low frequencies (40-60 kHz) and one at high frequencies (120-140 kHz). The bimodal nature of the clicks is very similar to the bimodal nature of clicks used by the false killer whale, *Pseudorca crassidens* (Au et al., 1995), and by the Atlantic bottlenose dolphin, *Tursiops truncatus*, (Moore and Pawloski, 1990). The spectral properties of the click will be discuss further when we examine some individual signals.

The properties of the echolocation signals shown in Fig. 3 is summarized by the curves in Fig. 6. The top graph is a plot of the interclick interval. The middle graph depicts f_p, the peak frequency (frequency at which the energy is maximum), f_o, the center frequency (frequency at the amount of energy on both side of it is equal) and BW, which is the root mean square bandwidth. The bottom graph depicts the peak-to-peak source level (sound pressure level of the echolocation signal measured at a distance 1 m from the animal) and the source energy flux density. The interclick interval in Fig. 6 varied little from about 36 to 46 ms and from 28 to 76 ms in Fig. 8. Since the echolocating dolphin whose signal are shown in Fig. 6 was between 1.2 and 5.9 m away from the array, the interclick interval data clearly show that the dolphin received an echo from the swimmer and array before emitting another signal. The two-way transit time for an echolocation signal to leave the dolphin, arrive at a target 5.9 m away and then return as an echo to the dolphin is only 7.9 ms.

The frequency plot in Fig. 6 indicates peak frequencies as high as 140 kHz. These peak frequencies are higher than the peak frequencies used by almost all other dolphins and porpoises that regularly emit whistles and emit short duration (5-7 cycles), broadband echolocation signals (Au, 1993). Peak

frequency is probably not the best frequency indicator for these bimodal signals, because the low and high frequency peaks are often very close in amplitude. Center frequency is probably a better descriptor of the frequency extend of bimodal signals. The center frequency plot of Fig. 6 indicate that most of the clicks had center frequencies between 80 to 100 kHz. The rms bandwidth in Fig. 6 varied between 32 and 46 kHz, with a cluster around 40 kHz. These bandwidths are much higher than bandwidths produced by other odontocetes (Au, 1993).

The final graph of Fig. 6 shows the source levels and source energy flux density of these two sequence of higher amplitude click signals. In this sequence, there most of the signals had peak-to-peak source levels between 200 and 205 dB re 1 Pa. The largest signals received had a source level of 208 dB (1996 data) and 210 dB (1997). These levels are not quite as high as those reported for *Tursiops truncatus* (Au et al., 1974), *Delphinapterus leucas* (Au et al., 1985) and *Pseudorca crassidens* (Thomas and Turl, 1990). These latter animals emitted signals with peak-to-peak source levels greater than 220 dB. However, these animals were involved in a target detection task with a target that were up to 100 plus meters away. The dolphins in this study were much closer to their targets (swimmer and array) and the target (wet-suited swimmer) was much larger than the 7.62 cm diam. sphere used with the other animals.

The waveform and frequency spectrum of three signals are shown in Fig 7, 8 and 9. The signals were all of very short duration, on the order of 60-70 s, and most were bimodal. The frequency spectra have a bimodal characteristic with a high frequency peak between 125-140 kHz and a low frequency peak between 45 - 70 kHz. Most of the low amplitude signals had a low peak frequency similar to the signal in Fig. 9. Higher amplitude signal sometimes had both a low and high peak frequency, but all these signals had a very small difference in the amplitudes of the low and high frequency as in Fig. 8.

DISCUSSION AND CONCLUSION

The echolocation signals used by *Stenella frontalis* are similar in many ways to echolocation signals of other odontocetes that can also whistle. The bandwidth or frequency extent of the signals seem to be slightly larger than previously measured for species such as *Tursiops truncatus* (Au, 1993), *Delphinapterus leucas* (Au et al., 1985), and *Pseudorca crassidens* (Thomas and Turl, 1990; Au et al., 1995).

The technique of using a multi-element array system along with video recording of underwater orientations, although not successful in acquiring signals from bottom foraging dolphins, is an excellent method to accurately measure echolocation signals from free-swimming dolphins. The use of this small base-line array of hydrophones has been shown to be useful in recording echolocation signals of wild dolphins. Both the location of the echolocating animals relative to the position of the array can be estimated and the orientation of the animal when it is pointed at the array can be verified in one plane (horizontal plane in our case). In this study, we used a line array of three hydrophones in which the hydrophones were separated by 30 cm and a second symmetrical star configuration array with four hydrophones spaced 45.7 cm. With such arrays, the location of an echolocating animals in 3-dimensional space can be estimated. If the dolphin is oriented at the center hydrophone, the relative amplitudes of the signals received by the 4 hydrophones could be used able to verify the orientation.

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Figure Captions

Fig.1 Schematic of the line array of three hydrophones and video camera supported by a float.

Fig.2 Geometry for localization of an echolocating dolphin.

Fig.3 First sequence of consecutive clicks received simultaneously by the three hydrophones.

Fig.4 Second sequence of consecutive clicks received simultaneously by the three hydrophones.

Fig.5 Spectrogram of the click sequence of Fig. 3. The largest amplitude signal from the three hydrophones for each click was used to compute the spectrogram.

Fig.6 A summary of the properties of the signals of Fig. 3.

Fig.7 Signal waveform and frequency spectrum of an echolocation signal with a high peak frequency.

Fig.8 Signal waveform and frequency spectrum of an echolocation signal with a strong bimodal frequency spectrum.

Fig.9 Signal waveform and frequency spectrum of an echolocation signal with a low peak frequency.

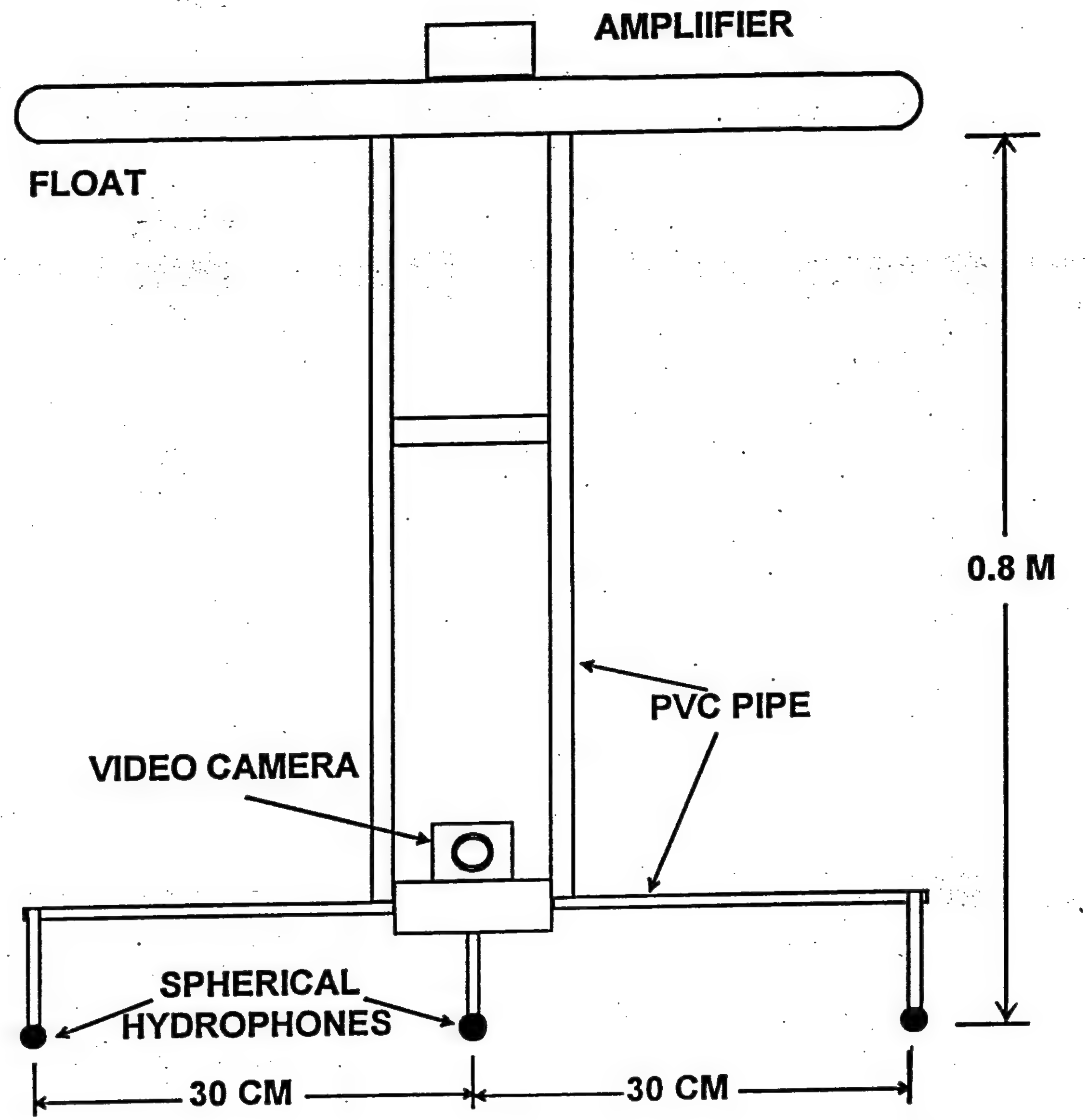

AMPLIIFIER
FLOAT
0.8 M
PVC PIPE
VIDEO CAMERA
SPHERICAL
HYDROPHONES
30 CM
30 CM

Fig. 1

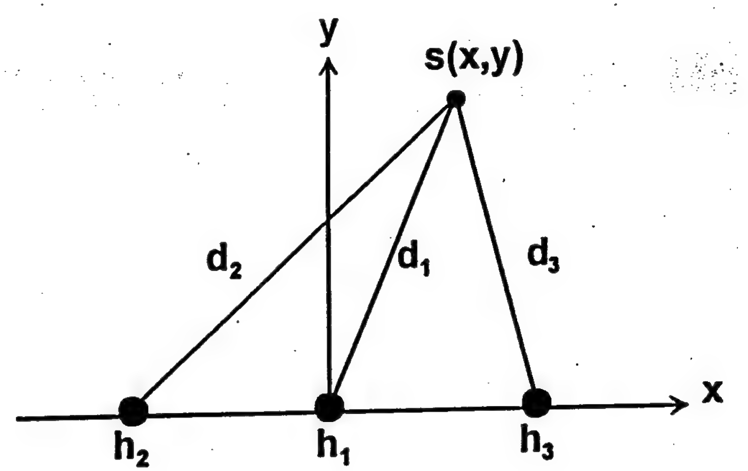


Fig. 2

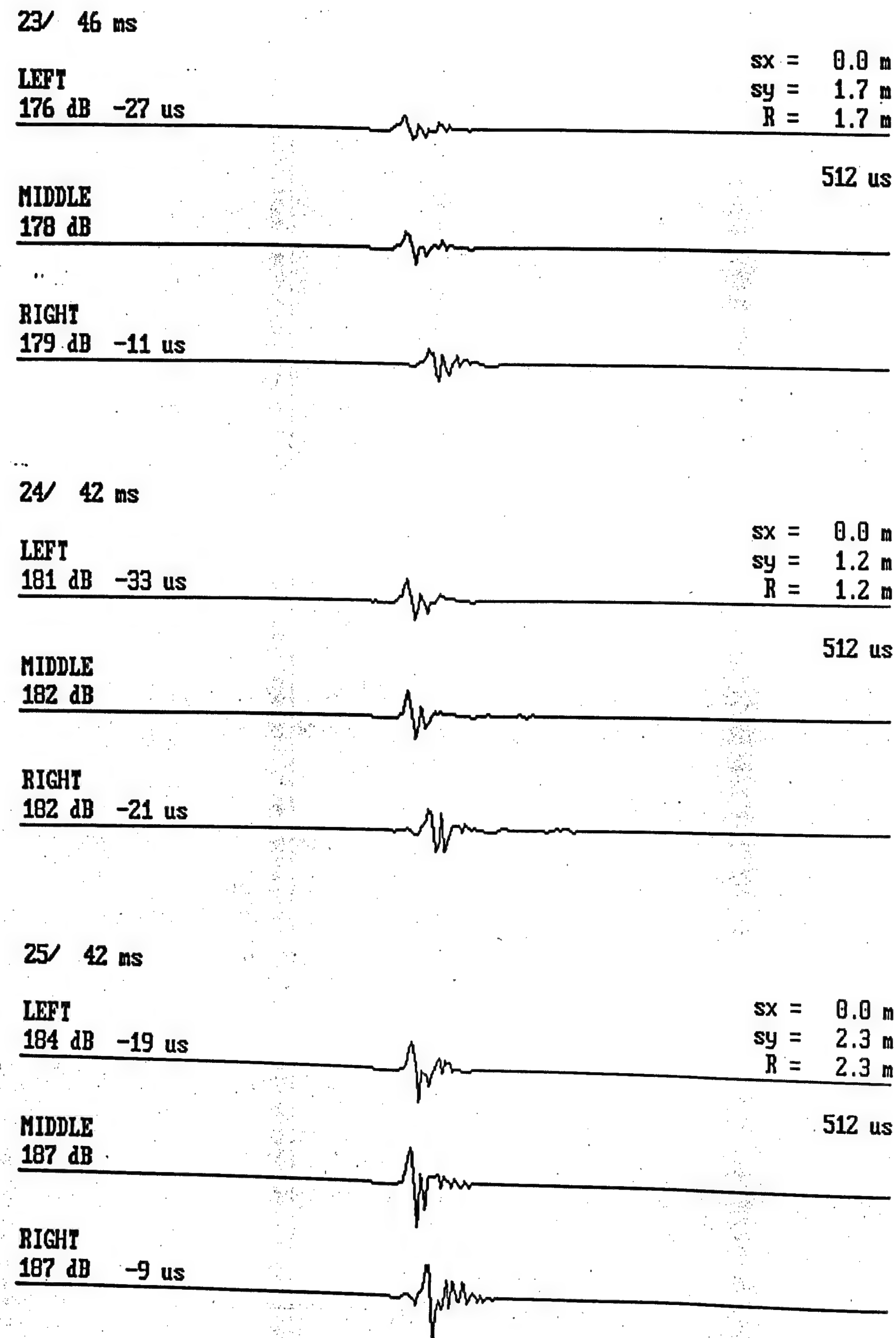

23/ 46 ms
LEFT
176 dB -27 us
sx = 0.0 m
sy = 1.7 m
R = 1.7 m
512 us
MIDDLE
178 dB
RIGHT
179 dB -11 us
24/ 42 ms
LEFT
181 dB -33 us
sx = 0.0 m
sy = 1.2 m
R = 1.2 m
512 us
MIDDLE
182 dB
RIGHT
182 dB -21 us
25/ 42 ms
LEFT
184 dB -19 us
sx = 0.0 m
sy = 2.3 m
R = 2.3 m
512 us
MIDDLE
187 dB
RIGHT
187 dB -9 us

Fig. 3

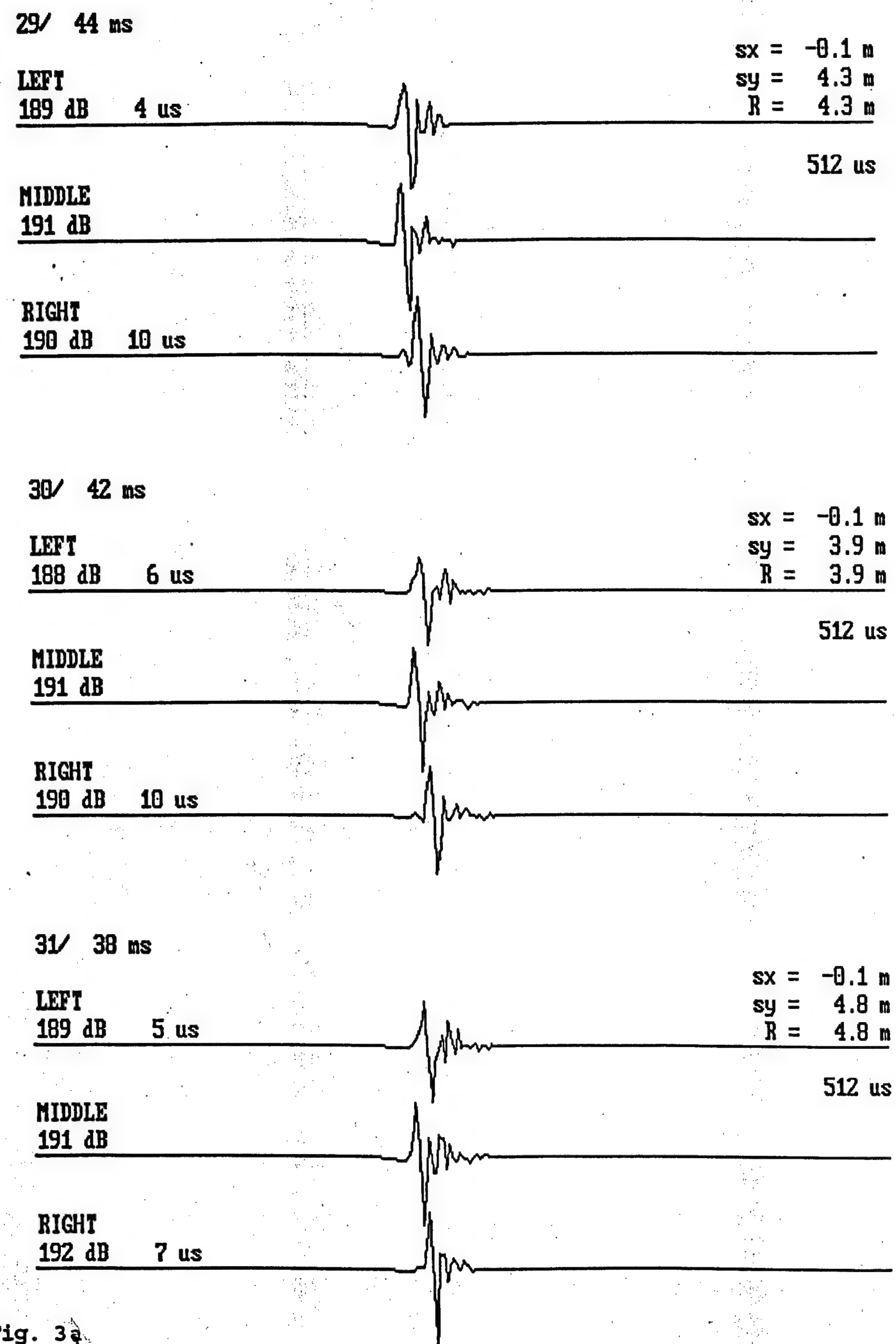

29/ 44 ms
sx = -0.1 m
sy = 4.3 m
R = 4.3 m
LEFT
189 dB 4 us
512 us
MIDDLE
191 dB
RIGHT
190 dB 10 us
30/ 42 ms
sx = -0.1 m
sy = 3.9 m
R = 3.9 m
LEFT
188 dB 6 us
512 us
MIDDLE
191 dB
RIGHT
190 dB 10 us
31/ 38 ms
sx = -0.1 m
sy = 4.8 m
R = 4.8 m
LEFT
189 dB 5 us
512 us
MIDDLE
191 dB
RIGHT
192 dB 7 us

Fig. 3a

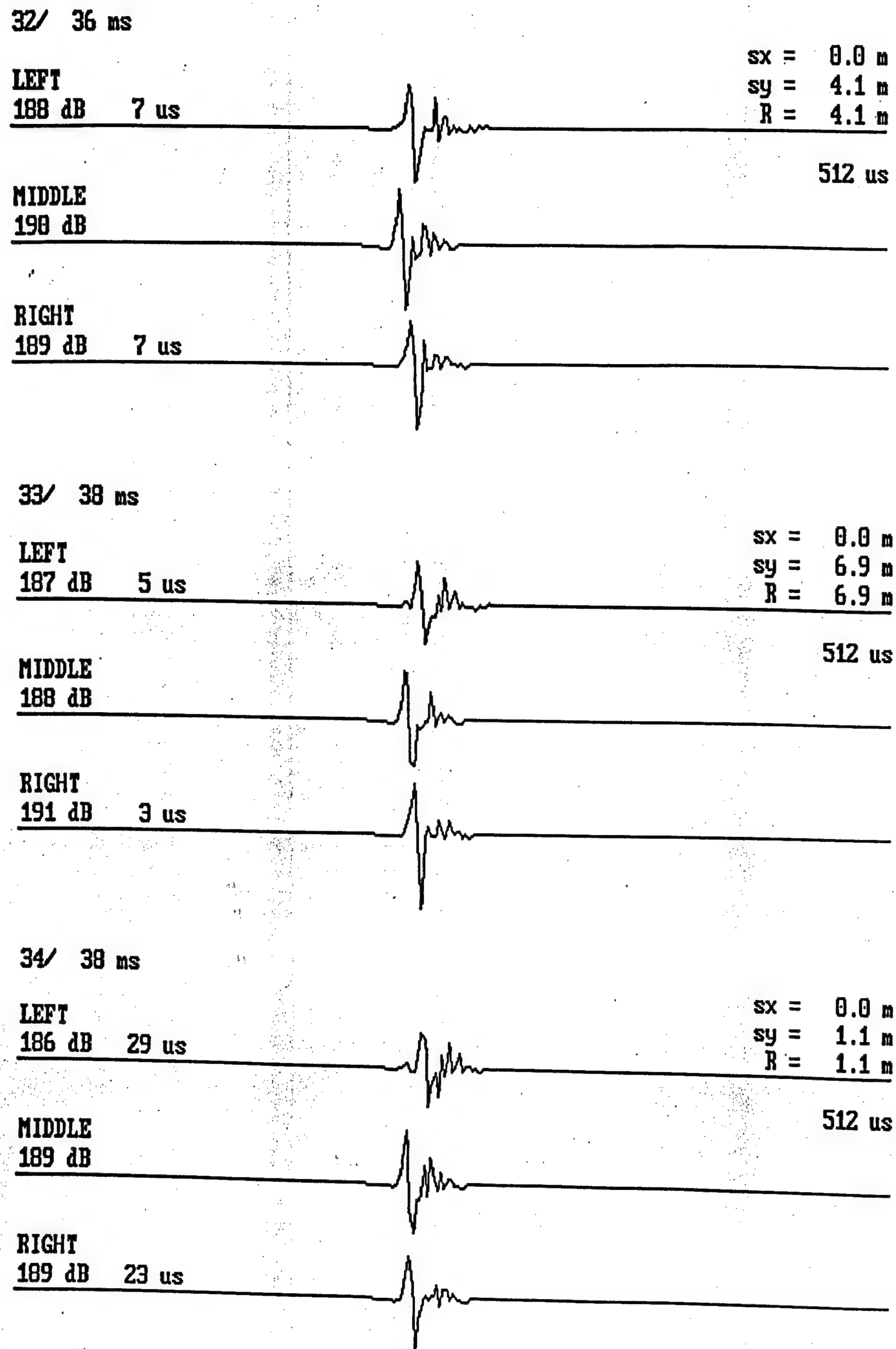

32/ 36 ms
LEFT
188 dB 7 us
sx = 0.0 m
sy = 4.1 m
R = 4.1 m
512 us
MIDDLE
190 dB
RIGHT
189 dB 7 us
33/ 38 ms
LEFT
187 dB 5 us
sx = 0.0 m
sy = 6.9 m
R = 6.9 m
512 us
MIDDLE
188 dB
RIGHT
191 dB 3 us
34/ 38 ms
LEFT
186 dB 29 us
sx = 0.0 m
sy = 1.1 m
R = 1.1 m
512 us
MIDDLE
189 dB
RIGHT
189 dB 23 us

Fig. 3b

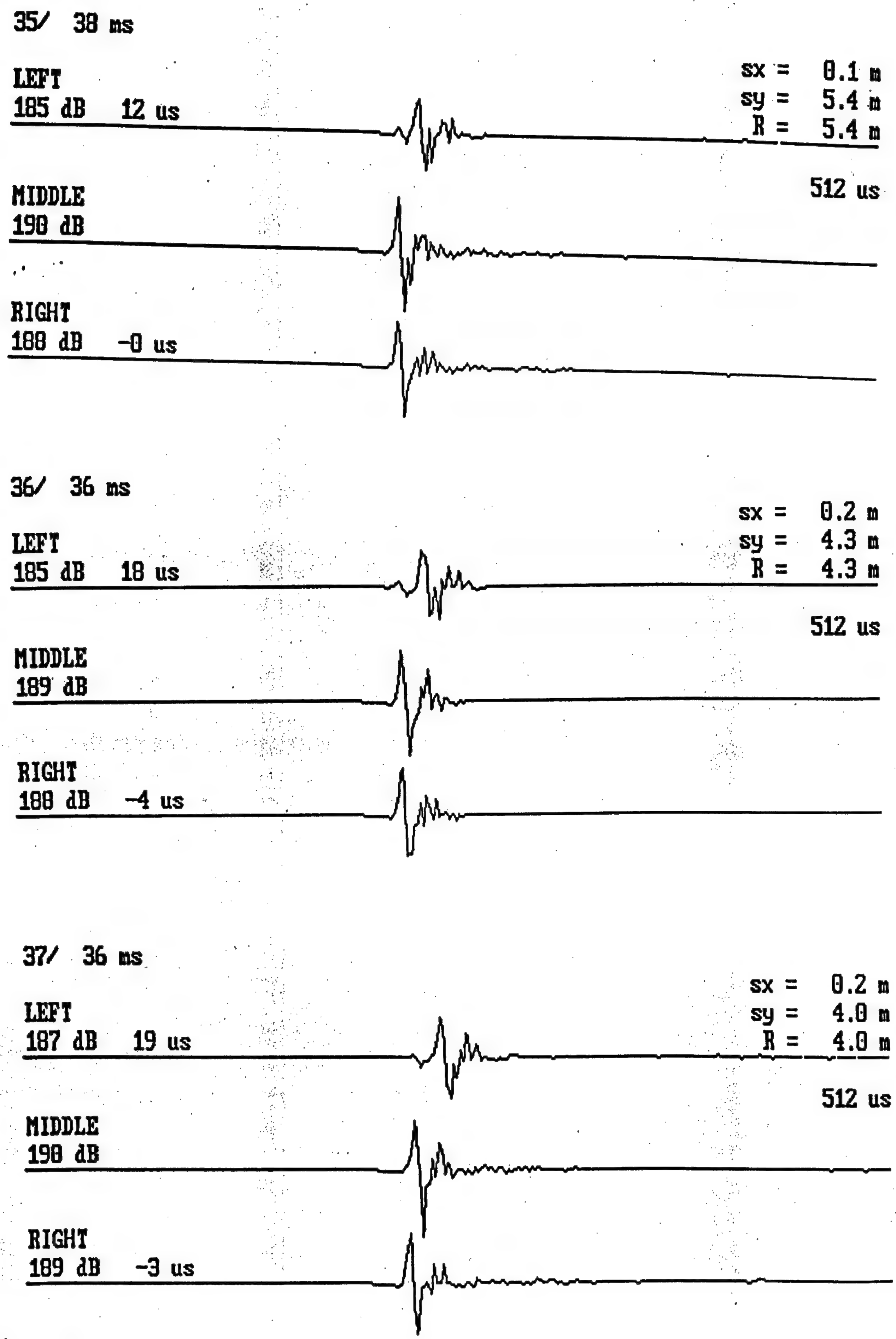

35/ 38 ms
LEFT
185 dB 12 us
sx = 0.1 m
sy = 5.4 m
R = 5.4 m
512 us
MIDDLE
190 dB
RIGHT
188 dB -0 us
36/ 36 ms
LEFT
185 dB 18 us
sx = 0.2 m
sy = 4.3 m
R = 4.3 m
512 us
MIDDLE
189 dB
RIGHT
188 dB -4 us
37/ 36 ms
LEFT
187 dB 19 us
sx = 0.2 m
sy = 4.0 m
R = 4.0 m
512 us
MIDDLE
190 dB
RIGHT
189 dB -3 us

Fig. 3c

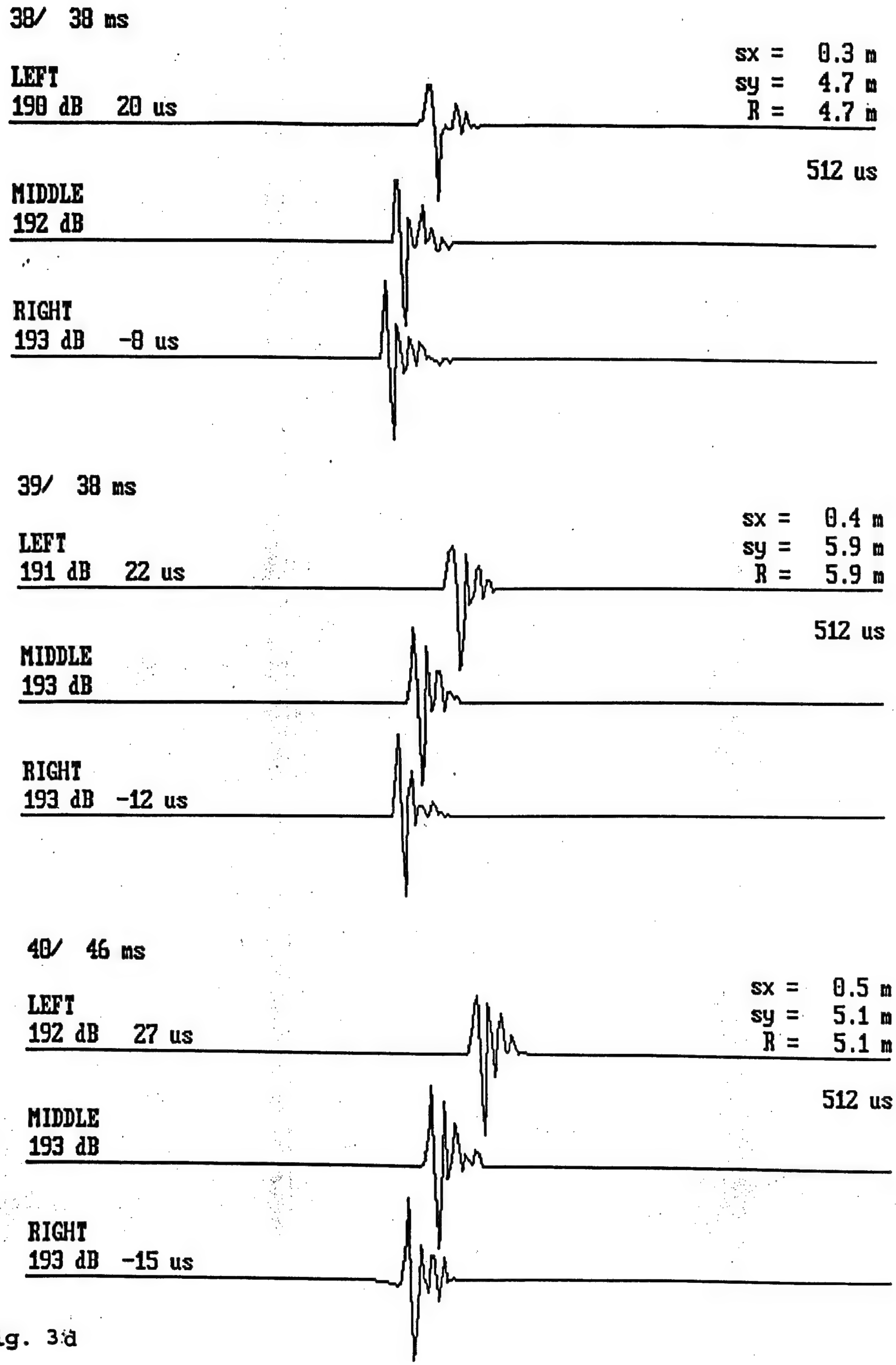

38/ 38 ms
LEFT
190 dB 20 us
sx = 0.3 m
sy = 4.7 m
R = 4.7 m
512 us
MIDDLE
192 dB
RIGHT
193 dB -8 us
39/ 38 ms
LEFT
191 dB 22 us
sx = 0.4 m
sy = 5.9 m
R = 5.9 m
512 us
MIDDLE
193 dB
RIGHT
193 dB -12 us
40/ 46 ms
LEFT
192 dB 27 us
sx = 0.5 m
sy = 5.1 m
R = 5.1 m
512 us
MIDDLE
193 dB
RIGHT
193 dB -15 us

Fig. 3d

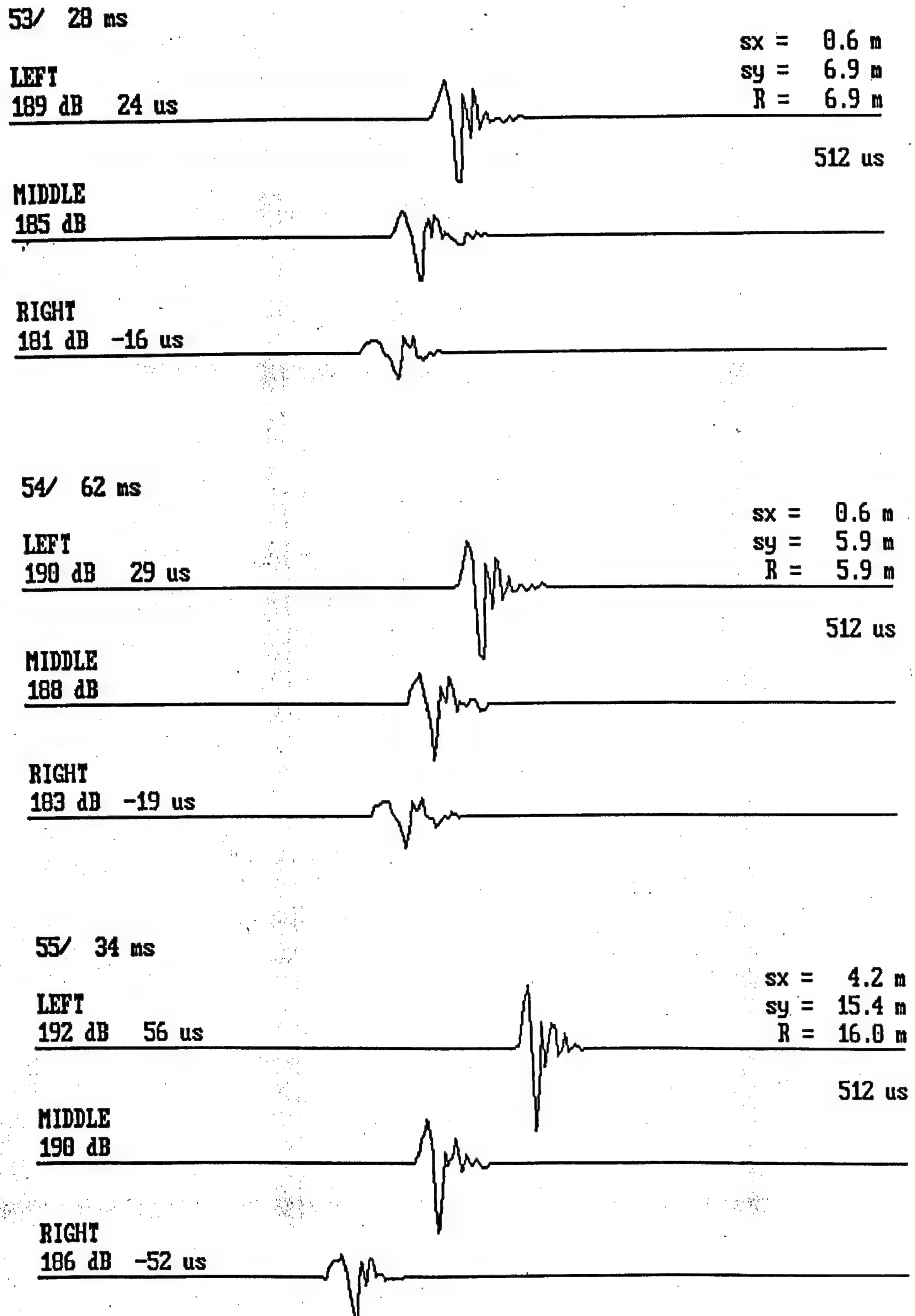

53/ 28 ms
LEFT
189 dB 24 us
sx = 0.6 m
sy = 6.9 m
R = 6.9 m
512 us
MIDDLE
185 dB
RIGHT
181 dB -16 us
54/ 62 ms
LEFT
190 dB 29 us
sx = 0.6 m
sy = 5.9 m
R = 5.9 m
512 us
MIDDLE
188 dB
RIGHT
183 dB -19 us
55/ 34 ms
LEFT
192 dB 56 us
sx = 4.2 m
sy = 15.4 m
R = 16.0 m
512 us
MIDDLE
190 dB
RIGHT
186 dB -52 us

Fig. 4a

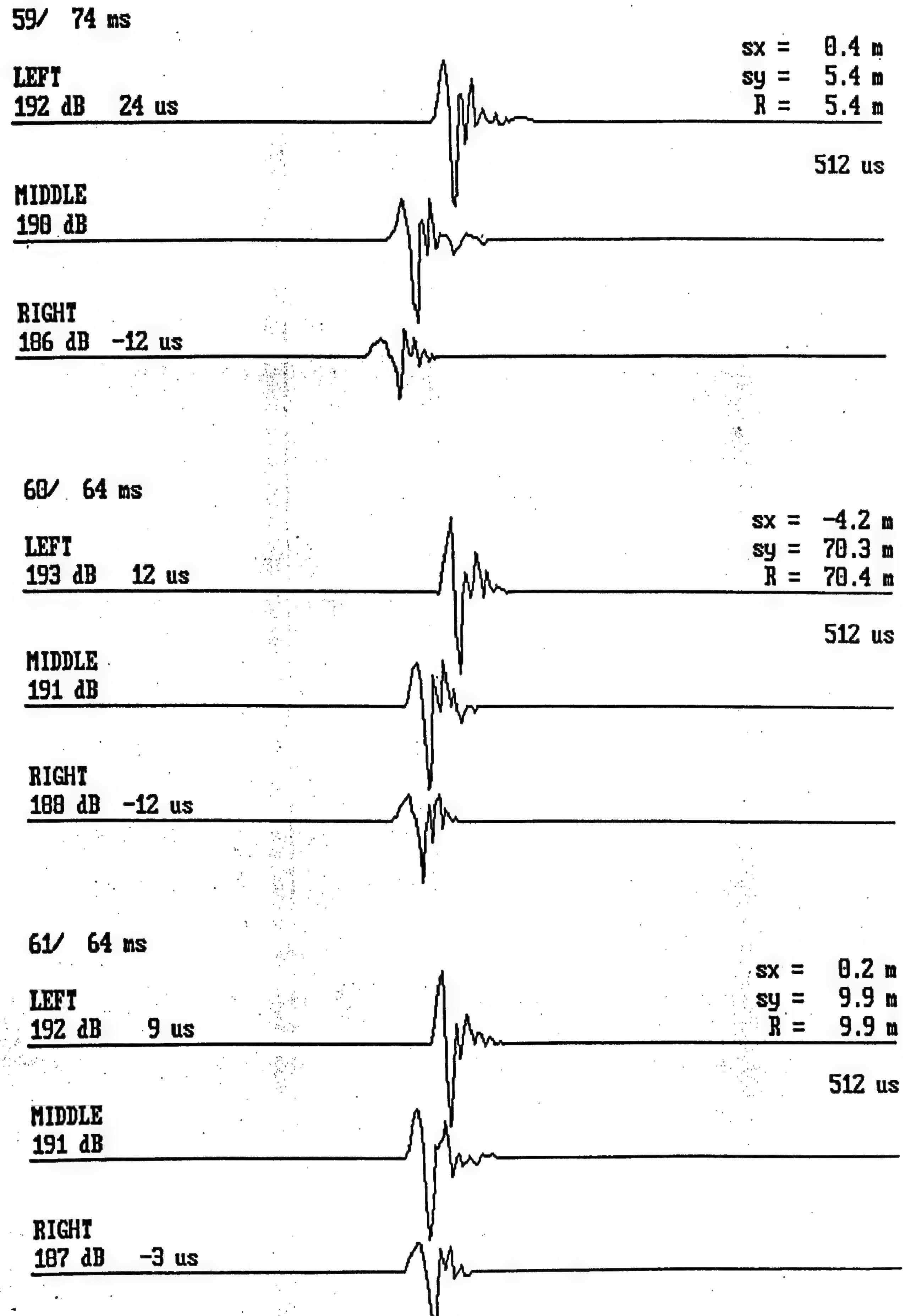

59/ 74 ms
sx = 0.4 m
sy = 5.4 m
R = 5.4 m
LEFT
192 dB 24 us
512 us
MIDDLE
190 dB
RIGHT
186 dB -12 us
60/ 64 ms
sx = -4.2 m
sy = 70.3 m
R = 70.4 m
LEFT
193 dB 12 us
512 us
MIDDLE
191 dB
RIGHT
188 dB -12 us
61/ 64 ms
sx = 0.2 m
sy = 9.9 m
R = 9.9 m
LEFT
192 dB 9 us
512 us
MIDDLE
191 dB
RIGHT
187 dB -3 us

Fig. 4b

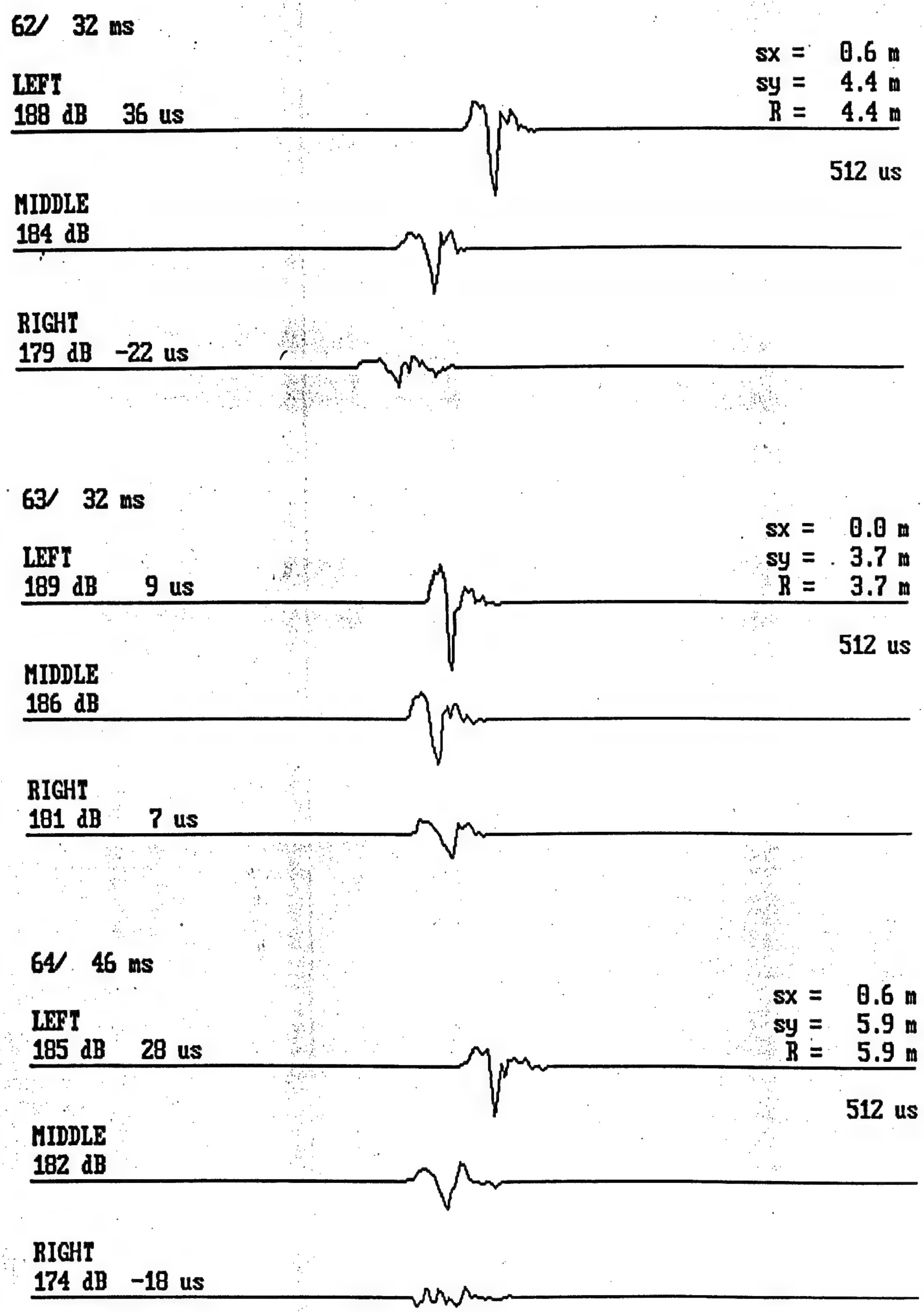

62/ 32 ms
sx = 0.6 m
sy = 4.4 m
R = 4.4 m
LEFT
188 dB 36 us
512 us
MIDDLE
184 dB
RIGHT
179 dB -22 us
63/ 32 ms
sx = 0.0 m
sy = 3.7 m
R = 3.7 m
LEFT
189 dB 9 us
512 us
MIDDLE
186 dB
RIGHT
181 dB 7 us
64/ 46 ms
sx = 0.6 m
sy = 5.9 m
R = 5.9 m
LEFT
185 dB 28 us
512 us
MIDDLE
182 dB
RIGHT
174 dB -18 us

Fig. 4c

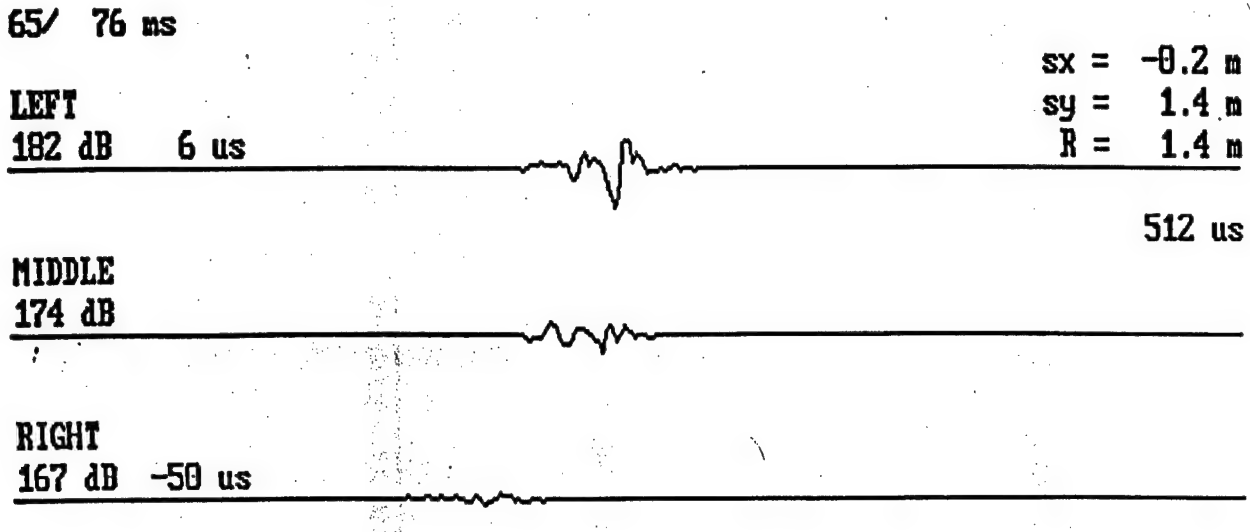

65/ 76 ms
sx = -0.2 m
sy = 1.4 m
R = 1.4 m
LEFT
182 dB 6 us
512 us
MIDDLE
174 dB
RIGHT
167 dB -50 us

Fig. 4a

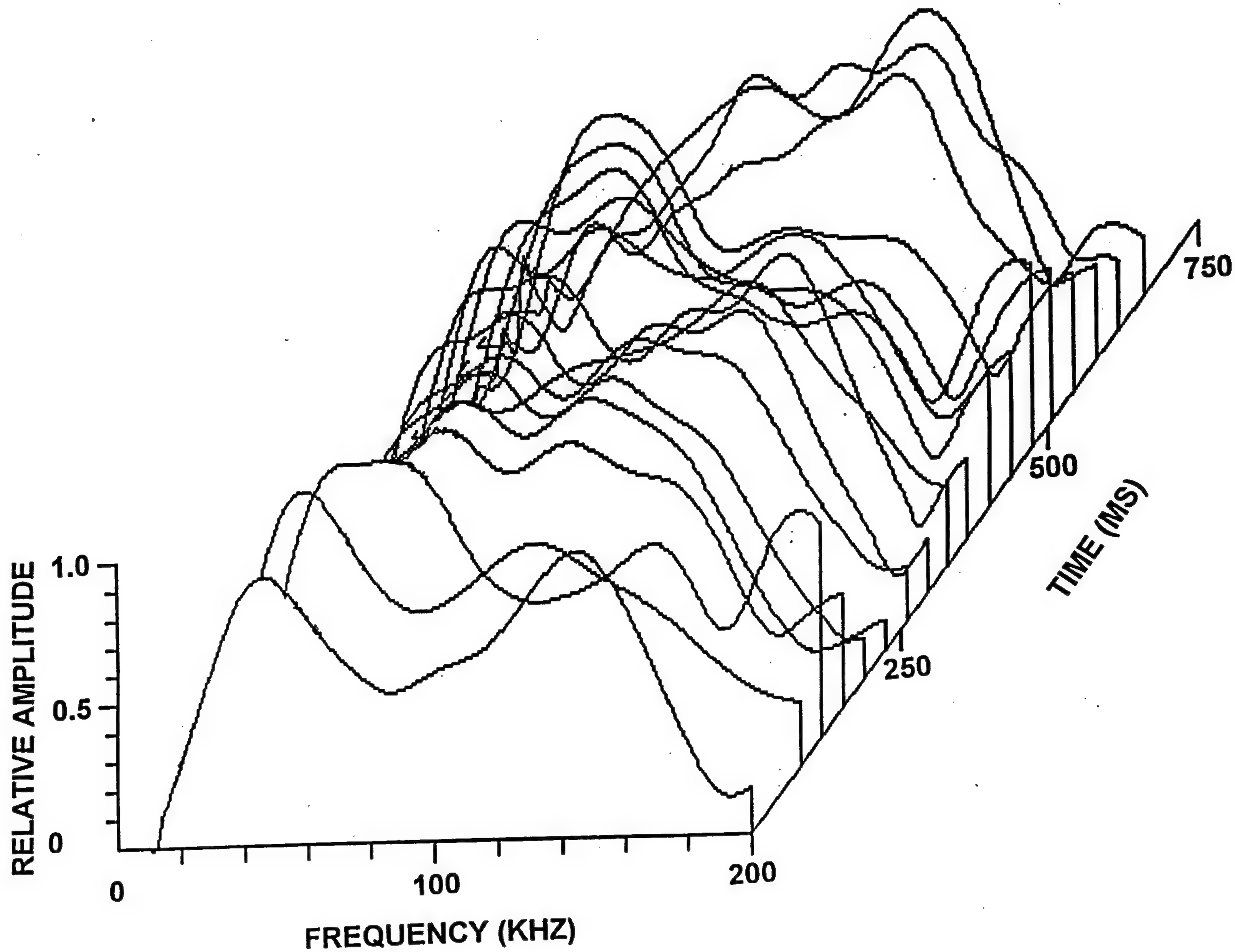

RELATIVE AMPLITUDE
1.0
0.5
0
0
100
200
FREQUENCY (KHZ)
250
500
750
TIME (MS)

Fig. 5

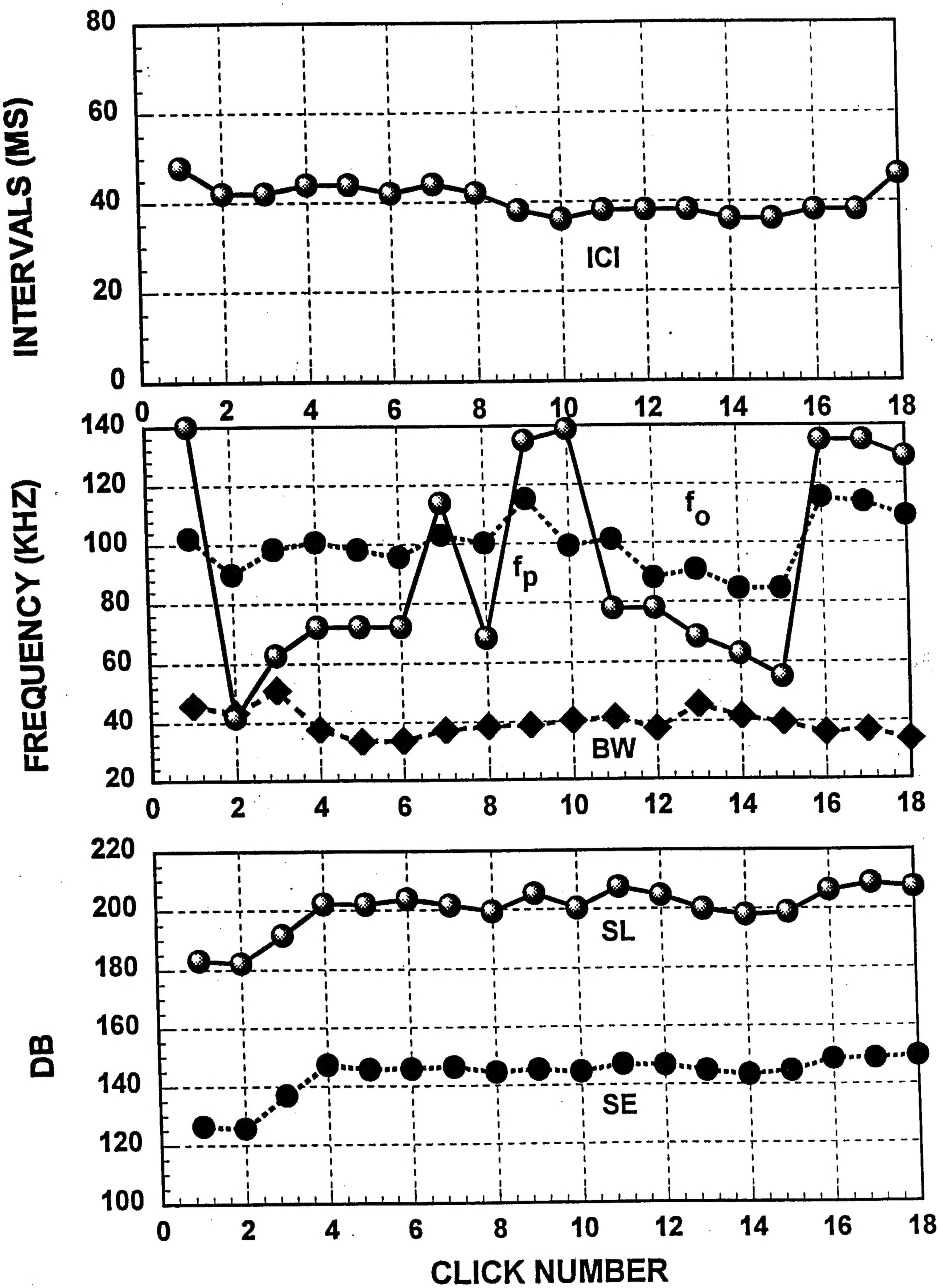
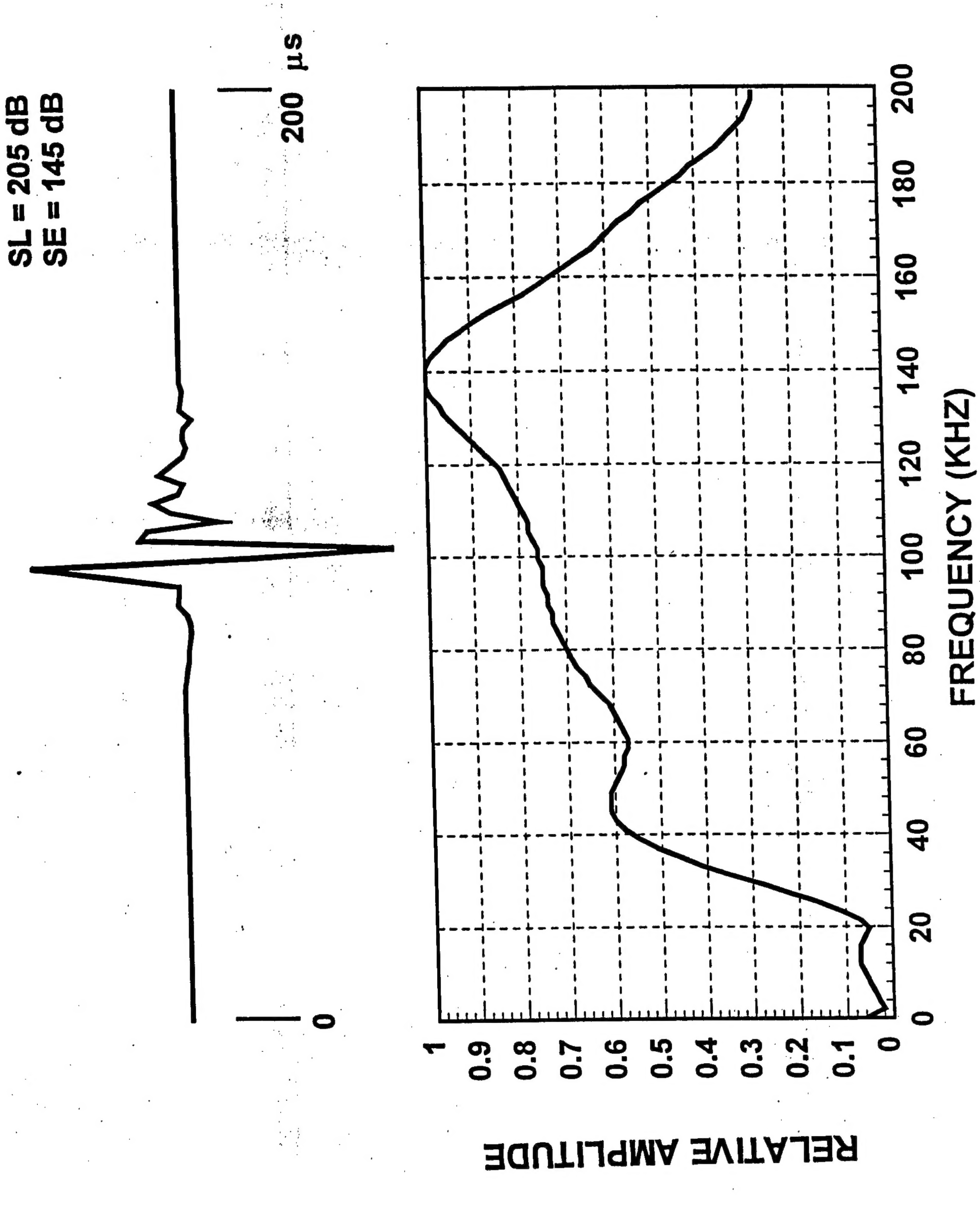


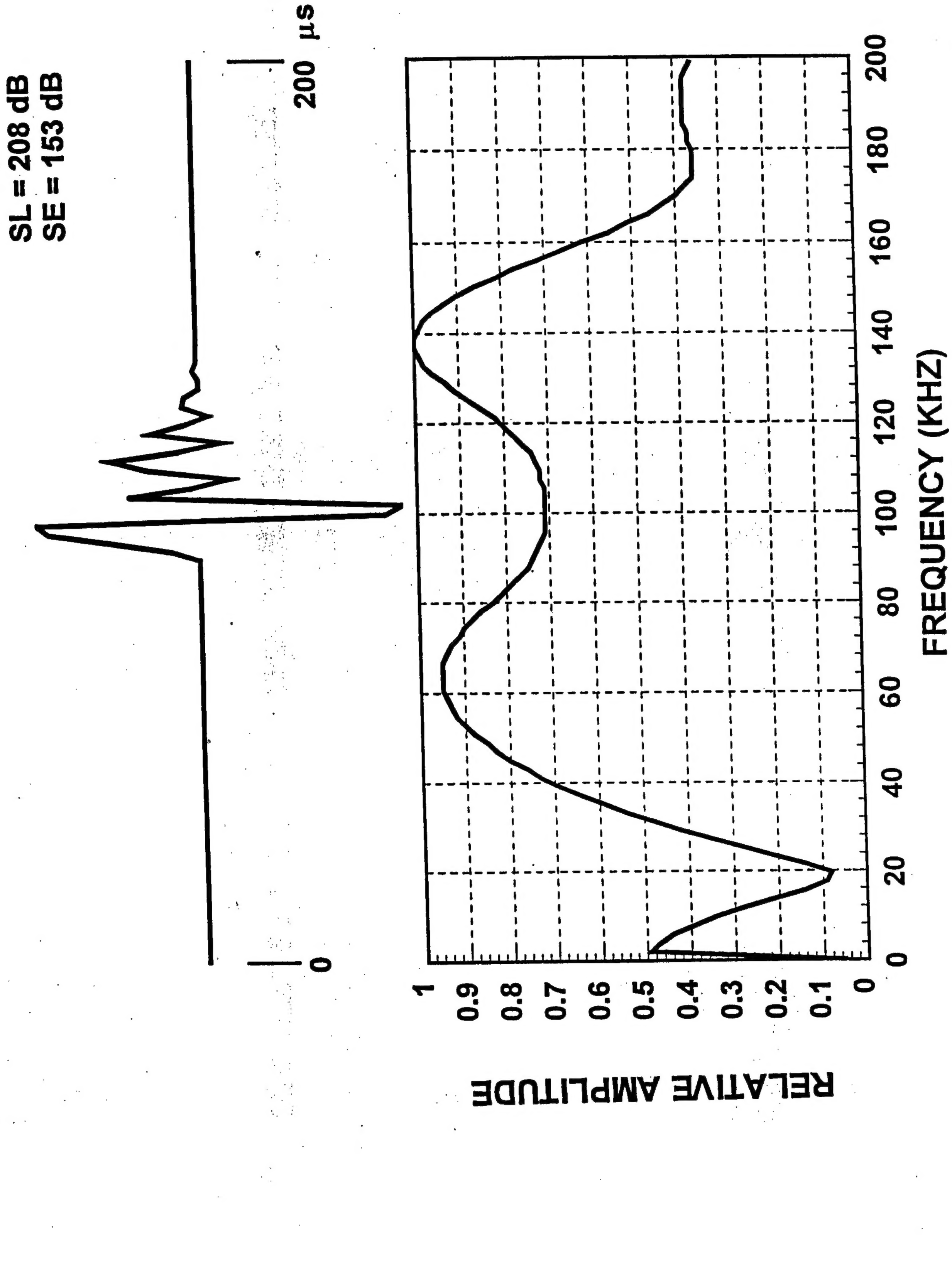
Fig. 6

Fig 7



SL = 205 dB
SE = 145 dB
0
200 µs
RELATIVE AMPLITUDE
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
140
160
180
200
FREQUENCY (KHZ)

Fig 8



SL = 208 dB
SE = 153 dB
0
200 µs
RELATIVE AMPLITUDE
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
140
160
180
200
FREQUENCY (KHZ)

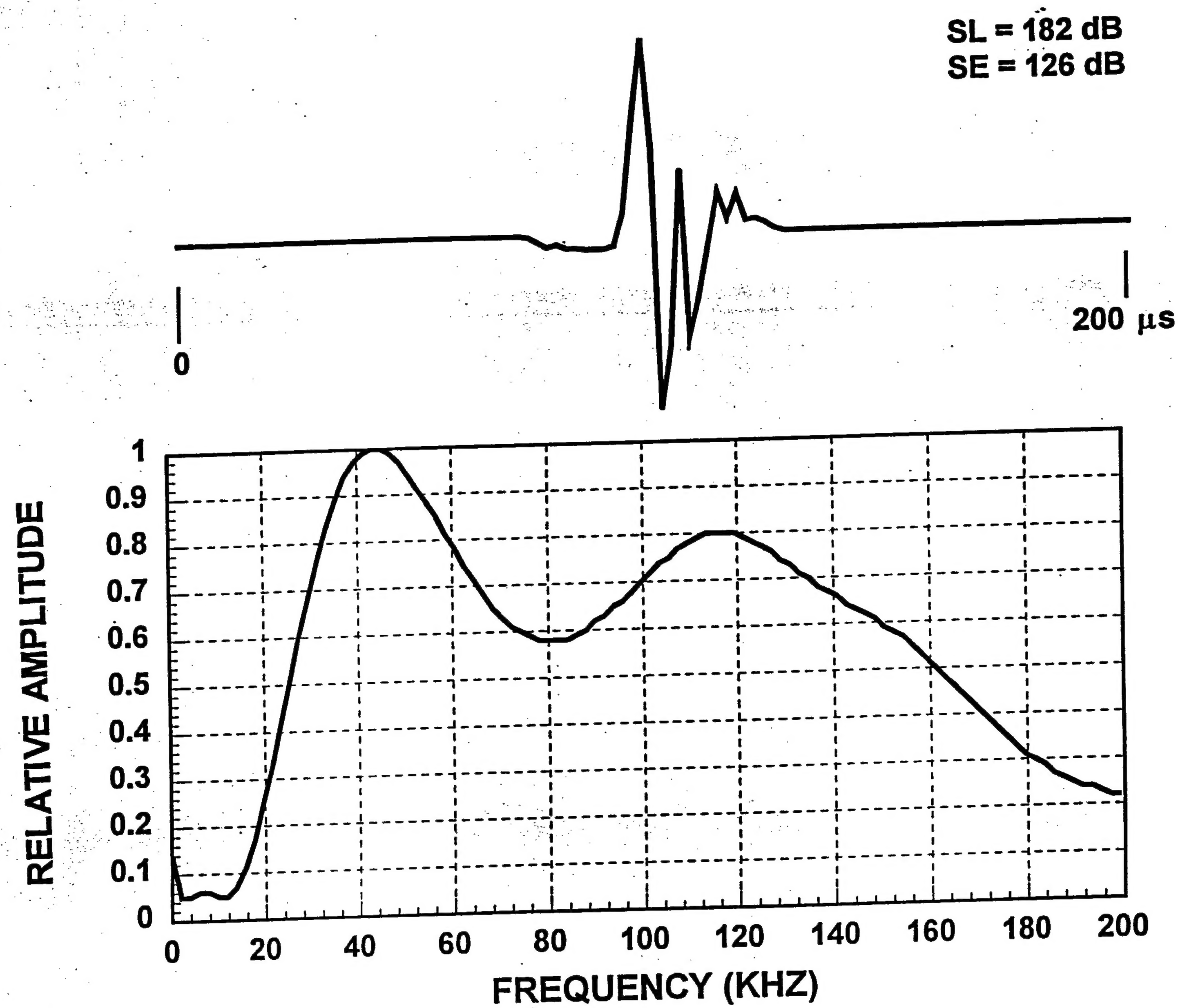

SL = 182 dB
SE = 126 dB
0
200 µs
RELATIVE AMPLITUDE
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
160
180
200
FREQUENCY (KHZ)

Fig 9